Evaluating Epoxy Debonding In Bonded Insulated Rail Joints

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Outline

• Problem definition
• Characterizing the debonded region
• Estimating the debonded area visually
• Assessing the effect of debonding on track stiffness
• Conclusions and future research opportunities
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Problem definition

- Insulated joints (IJ’s)
- Bonded insulated joints
- IJ failure modes
- Progressive epoxy debonding
Insulated rail joint (IJ)

- Insulated joints used to isolate adjacent track circuits
- Traditional design: bolted rail joint with insulators
Bonded insulated rail joint

- Insulators glued to both joint bar and rail
  - Better transfer of shear and tensile stresses
  - Better resistance to CWR thermal stresses
  - Less deflection under vertical loads

Not shown: bolt shanks encased in insulating thimbles
Bonded insulated rail joint
IJ failure

- AAR / TTCI study: mean IJ life < 200 MGT in heavy axle load environment
  - Shorter than any other track component except high-angle crossing diamonds
  - Direct costs: $1,000’s per mile per year for lines with heavy traffic
  - Indirect costs from traffic disruption

IJ failure modes

- Electrical failure: metal surfaces come into contact
  - Worn or cracked insulator, rail end batter
  - Can be intermittent, hard to detect
- Mechanical failure: cracked or missing bolts, crack joint bars, bolt hole cracks in rail, battered rail ends, excessive shelling on rail head
  - All the reasons industry moved away from jointed rail!
Progressive epoxy debonding

- Many problems appear to begin with deterioration in the epoxy that holds the joint together
- “Progressive epoxy debonding”: some of the epoxy comes unstuck from the rail, joint bar, or both
  - Begins near endpost (center of joint)
  - Grows outward towards edges of joint bar
  - Gradual reduction in stiffness and strength of epoxy bond
Complete epoxy failure

- As debonded region grows, shear strength of the bond decreases
- With enough debonding and high enough longitudinal loads, remaining bond breaks or insulator ruptures and the rails slip relative to joint bars
  - “Complete failure of the epoxy bond”
  - Reverts to bolted joint
- Shear stress in bolts and bolt holes, increased deflections, wear on insulators, variable-size gap between rail ends
Complete epoxy failure
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• **Characterizing the debonded region**
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Characterizing the debonded region

- Test setup
- Inspecting disassembled IJ’s
- Ambiguity; Inclusive ($A_i$) and Strict ($A_s$) measurements of debonded area
- Shape of debonded region
Test setup

• Collected 6 IJ’s with varying amounts of debonding
  – Four railroads, two regions, and two suppliers
  – Rail section either 132RE or 136RE
  – 6-bolt, 36” joint bars with holes spaced 2.5”-6”-6”-7”-6”-6”-2.5”
  – Joint bars varied by supplier
  – Materials, assembly differed by supplier
• All removed from track for unknown reasons after unknown traffic
Inspecting disassembled IJ’s

• When joint bars are removed from rails (not easy!), dark, rusty areas indicate debonded regions
Inspecting disassembled IJ’s

• Estimated area with a series of linear measurements from endpost to beginning of intact epoxy bond
Ambiguity

- Difficult to tell whether some areas were debonded
  - Speckled light and dark; dark but not rusty
- Two different measurements of debonded area:
  - “Inclusive” area ($A_i$) includes ambiguous regions
  - “Strict” area ($A_s$) only includes regions with heavy, consistent rust or dirt
  - Inclusive debonded area $A_i$ between 5% and 280% bigger than Strict area $A_s$
Ambiguity

INCLUSIVE

STRICT
Shape of debonded region

- Debonded region tends to extend further along top and bottom sections of interface – “U” or “V” shape
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Estimating the debonded area visually

- Visual metrics $V_m$ and $V_d$
- Correlations between those metrics and debonding
- Estimating debonded area from $V_d$
Visual metrics $V_m$ and $V_d$

- Progressive epoxy debonding occurs mainly on hidden surfaces; only the edges of insulator layer are visible in an in-track IJ
- Practitioners estimate extent of debonding by examining these edges. Does this work?
- Two metrics adopted
  - $V_m$: Extent of missing top edge of insulator layer
  - $V_d$: Extent of damaged (missing or loose) top edge of insulator layer
Visual metrics $V_m$ and $V_d$
Visual metrics $V_m$ and $V_d$
Visual metrics $V_m$ and $V_d$
Visual metrics $V_m$ and $V_d$
$V_m$, $V_d$ and debonding
Estimating debonding from $V_d$

- $V_d$ better than $V_m$ for estimating debonded area
  - $V_m$ can be zero with small / moderate debonding
  - Even with extensive debonding, $V_d$ correlates better
  - Disadvantage: $V_d$ harder to measure, more subjective and judge
Estimating debonding from $V_d$

- 80% Confidence interval for whole joint:
  
  $A_i = V_d \times 206 \text{ mm} \pm 27,000 \text{ mm}^2$
  
  $A_s = V_d \times 161 \text{ mm} \pm 11,000 \text{ mm}^2$

- “Unofficial” 80% C.I. for a single rail / joint bar interface:
  
  $A_i = V_d \times 201 \text{ mm} \pm 10,000 \text{ mm}^2$
  
  $A_s = V_d \times 159 \text{ mm} \pm 6,000 \text{ mm}^2$

  - Not enough data to prove certain statistical assumptions; use with caution
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Assessing the effect of debonding on track stiffness

• Test setup
• Joint stiffening, endpost stress, bilinear spring stiffness
• “Rotational spring” model for characterizing joint stiffness
• Spring stiffness vs. debonding
• Effects on in-track IJ
Test setup

• Same 6 IJ specimens as in previous test
  – Varying amounts of progressive epoxy debonding
• 3 additional samples
  – 2 new, unused control specimens (from different suppliers)
  – 1 specimen with complete epoxy failure
3-point bending tests

- IJ plug simply supported
- Applied load at joint center
- Measured deflection at joint center
Bilinear stiffness, joint stiffening, rail head compression at endpost
Bilinear stiffness, joint stiffening, rail head compression at endpost

- Hypothesis: increases resistance to deflection at high loads comes from compressive stresses developing in the railhead at the endpost

- Test: apply strain gages to several specimens
Bilinear stiffness, joint stiffening, rail head compression at endpost
Joint stiffening in track (?)

- Compressive rail head stresses wouldn’t have much effect under typical 160-kN static wheel load
- Our static model doesn’t necessarily reflect what would happen under higher dynamic wheel loads
- Longitudinal tension in the rail might prevent compressive stresses from developing in rail head
- Conservative approach: assume no stiffening
  – Assume joint stiffness is always that indicated by the response at low static load levels
“Rotational spring” model of joint

- Cox and Kerr, University of Delaware (1993)
- Two beams (the rails) connected by a rotational spring (the joint)
  - Rail ends deflect downward by equal amounts
  - Relative rotation between rail ends resisted by spring
- Stiffness of the joint characterized by a single parameter (the rotational spring stiffness)
  \[ M = s\Delta(y') \]
“Rotational spring” model of joint

Continuous rail

Stiff joint

Loose joint

P
## Rotational spring stiffnesses

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$s_b$ (kN-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA1</td>
<td>17,400</td>
</tr>
<tr>
<td>TA1</td>
<td>9,600</td>
</tr>
<tr>
<td>TA2</td>
<td>8,200</td>
</tr>
<tr>
<td>TA3</td>
<td>5,600</td>
</tr>
<tr>
<td>CB1</td>
<td>18,700</td>
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<tr>
<td>TB1</td>
<td>12,900</td>
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<tr>
<td>TB2</td>
<td>17,000</td>
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<tr>
<td>TB3</td>
<td>5,200</td>
</tr>
<tr>
<td>TB4</td>
<td>3,300</td>
</tr>
</tbody>
</table>
**Spring stiffness vs. debonding**

- Even an IJ with complete epoxy failure has some stiffness, so decompose $s$ into $s = s_u + s_e$
  - $s_u = $ stiffness of an “unbound” joint
  - $s_e = $ increase in stiffness due to epoxy bond
  - Estimate $s_u = 3,300$ kN-m from 3-point bending test on a joint with complete epoxy failure
Spring stiffness vs. debonding

\[ S_e (kN-m \times 10^3) \]

\[ A_i (mm^2 \times 10^3) \]

\[ S_e (kN-m \times 10^3) \]

\[ A_s (mm^2 \times 10^3) \]
### 80% Confidence intervals for stiffness parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated value (kN-m)</th>
<th>Range (kN-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_e$ based on $A_i$</td>
<td>$15,000e^{-0.0102A_i}$ (1)</td>
<td>$\pm 1,800$</td>
</tr>
<tr>
<td>$s_e$ based on $A_s$</td>
<td>$14,700e^{-0.0150A_s}$ (1)</td>
<td>$\pm 1,300$</td>
</tr>
<tr>
<td>$s_u$</td>
<td>3,300</td>
<td>N/A</td>
</tr>
</tbody>
</table>

(1) $A_i$ and $A_s$ measured in mm$^2 \times 10^3$
Effect of loss of stiffness

- Lower spring stiffness leads to:
  - Higher deflections
  - Increased loads on the cross ties nearest the joint
  - Higher dynamic loads
- Increased damage to ballast and / or subgrade likely
- Increased damage to IJ itself (cracks, insulator wear, etc.) likely
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$A_i$ versus $A_s$

- Recall: $A_i$ (the “inclusive” debonded area) counted some ambiguous areas as debonded, while $A_s$ (the “strict” debonded area) did not.
- $A_s$ correlated better with both visual evidence of debonding and loss of joint stiffness.
- Not determined: which measurement is more indicative of longitudinal strength?
Debonding pattern

- Debonding tends to extend farther along top and bottom of interface (~30 mm on average)
- Tends to be more debonding on one end of the joint than the other
- No significant difference between gage and field side
Visual inspection

- Examine top edge of epoxy / insulator layer
- For best results, include places where the epoxy bead has started to separate from metal but not yet broken off
- For whole joint (80% confidence):
  \[ A_i = V_d \times 206 \text{ mm} \pm 27,000 \text{ mm}^2 \]
  \[ A_s = V_d \times 161 \text{ mm} \pm 11,000 \text{ mm}^2 \]
Effect of debonding on stiffness

- Ignoring any stiffening effects from compressive stresses in the railhead at the endpoint, the rotational spring stiffness parameter of an IJ is reduced by:
  - ~80% with complete epoxy failure
  - > 30% with 50,000 mm² of debonding (about 15% of total epoxy surface)
- Potential increase in dynamic load factors and load concentration on nearby ties
  - Accelerated ballast and subgrade degradation
Future research opportunities

- Similar experiments to determine relationship between debonded area and longitudinal epoxy strength
- Experimentally verified dynamic model that can account for debonding
- Effect of debonding on joint bar cracks
  - Dynamic loads increase
  - Reaction forces concentrated on nearby ties, so bending moment carried by joint bars decreases
  - Net effect unknown
Future research opportunities (cont)

• Study relationship between mechanical degradation and electrical failure

• Develop inexpensive, fully-automated systems for measuring both electrical integrity and mechanical condition of joint
  – Leave-in-place sensors vs. “inspection”
  – One leave-in-place system for measuring debonded area described in my thesis – needs more work
Big picture

- Make sure that all problems are being addressed
  - Dynamic load & effects on plates, fasteners, ties, ballast, subgrade, and wheels
  - Electrical failure
  - Cracks & derailment risks
- Alternatives to IJ’s
  - Jointless track circuits
  - Axle counters in lieu of track circuits
  - CBTC with GPS and / or location beacons
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